Spectral Analysis Software in Astronomical Research: Postprint

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Abstract

With the planning, implementation, and operation of large-scale spectroscopic survey projects, automatically analyzing, efficiently mining, and rapidly extracting information from massive numbers of celestial spectra to obtain effective physical parameters of astronomical objects has become a focal point for astronomers and an important topic in contemporary astronomical research. Most astronomical research is based on spectroscopic analysis, and the convenience and usability of various rapidly developing spectroscopic analysis tools significantly facilitate the investigation of characteristics of astronomical spectra. This paper describes several large-scale spectroscopic survey projects that have been completed, are currently operating, or will be launched domestically and internationally, and points out the important significance of applying spectroscopic analysis tools. Taking seven commonly used spectroscopic analysis software packages—VOSpec, VOSED, SpecView, Iris, SPLAT, CASSIS, and ASERA—as examples, this paper introduces the basic characteristics and main functions of spectroscopic analysis software, compares the similarities and differences in their application environments, and provides guidance and reference for astronomers in selecting and utilizing spectroscopic analysis tools.

Full Text

Application of Spectral Analysis Software in Astronomical Research

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Abstract

With the planning, implementation, and operation of large-scale spectroscopic survey projects, the automatic analysis, efficient mining, and rapid extraction of information from vast quantities of astronomical spectra to obtain effective physical parameters of celestial objects has become a focal point for astronomers and an important topic in contemporary astronomical research. Most astronomical research is based on spectral analysis, and the convenience and usability of various rapidly developing spectral analysis tools are of significant importance for exploring the characteristics of astronomical spectra. This paper describes several completed, ongoing, and upcoming large-scale spectroscopic survey projects both domestically and internationally, and points out the importance of applying spectral analysis tools. Taking SPLAT as an example, the basic features and main functions of spectral analysis software are introduced, while comparing the similarities and differences in application environments of commonly used spectral analysis software such as SpecView, VOSpec, VOSED, ASERA, and CASSIS, providing guidance and reference for astronomers to select and apply spectral analysis tools.

Introduction

The equivalent width or profile of spectral lines, magnetic fields, and motion velocities are among the physical parameters of celestial objects obtained through radiative transfer analysis. Astronomical spectra are patterns formed by collecting electromagnetic radiation from celestial objects with a spectrometer placed at the telescope focal plane and arranging it by wavelength. Using the information contained in astronomical spectra, the principles and methods of spectroscopy are applied to celestial objects to determine their physical properties and chemical composition. Astronomical spectral analysis includes two types: qualitative analysis and quantitative analysis. Qualitative analysis primarily involves spectral line identification, comparing the positions of known wavelength lines with those in astronomical spectra to identify the chemical elements producing the lines. Quantitative analysis includes measuring both the continuum and spectral lines of celestial objects. The former refers to measuring the intensity of the continuum at various wavelengths to obtain the continuous energy distribution, while the latter refers to measuring the intensity within spectral lines. Through these measurements, physical parameters such as temperature can be inferred.

With advances in space detection technology and astronomical discoveries, observations have expanded from visible light to all electromagnetic bands including infrared, forming full-band astronomical spectroscopy[1] and providing powerful observational means for exploring the physical nature of various celestial objects and phenomena. In the development of astronomy, over the past decade international large-scale spectroscopic survey projects have been carried out[2], including the 2-degree Field Galaxy Redshift Survey (2dF) conducted with the 3.9m Anglo-Australian Telescope, which obtained spectra of over 221,414 objects with good quality, and the Sloan Digital Sky Survey (SDSS), whose third phase (DR12) contains 12,311 effective spectra obtained using a 2.5m telescope in New Mexico.

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), also known as the Guo Shoujing Telescope, has released 3,275,942 spectra, including stellar spectra with signal-to-noise ratios greater than certain thresholds, providing stellar parameters and forming the world' s largest stellar parameter catalog. Astronomers are already planning next-generation large-scale spectroscopic surveys, developing giant telescopes primarily for detecting dark energy and dark matter, such as the Large Synoptic Survey Telescope (LSST) for finding small solar system objects, supernovae, and observing the Milky Way; the Wide Field Infrared Survey Telescope (WFIRST) for observing primarily in the near-infrared; and the European Space Agency' s planned Euclid mission to study the large-scale distribution of dark matter in the universe and confirm the nature of dark energy, also observing in optical bands.

As large-scale survey projects continue, spectral data is growing exponentially. It is clear that manual processing and analysis of spectra is no longer feasible, making the development of automated spectral analysis software essential. As the saying goes, "To do a good job, one must first sharpen one' s tools." Only with excellent spectral analysis tools can astronomers conveniently analyze and study spectra, thereby improving work efficiency and scientific output.

A good spectral analysis software should be able to query spectral data from different surveys and data types, visualize and analyze spectra individually or in batches, and study spectral energy distributions, which is crucial for researching the potential astrophysical information contained in spectra. Due to differences in telescopes and research objectives, different functional spectral analysis software needs to be developed. Today, with interdisciplinary integration, astronomers' spectral processing needs are met thanks to computer technology. Many astronomical research teams continuously develop new spectral analysis software, such as those from the International Virtual Observatory Alliance[3] (IVOA). Mature and widely used spectral analysis software can be simply classified by function: (1) Spectral query: TOPCAT, CASSIS, VOSED, SPLAT, Datascope, SpecView, VOServices, VOSpec, Data Discovery Tool, VirGO; (2) Spectral energy distribution: CASSIS, SPLAT, SpecView, VOServices, VOSpec, Gaia; (3) SED analysis software: VOSA, VOSED, VOSpec, Iris, GOSSIP. Here we focus on introducing Aladin, CASSIS, and spectral visualization tools.

Commonly Used Spectral Analysis Software

2.1 VOSpec

VOSpec[4] is a multi-band spectral analysis tool developed by the European Space Agency' s Virtual Observatory team. It has powerful data organization functions, allowing users to conveniently retrieve data from spectral libraries worldwide by object name or coordinates using the Simple Spectral Access Protocol (SSAP). The software can access observational spectral data, theoretical model data, and line lists. Its standard functions fall into two categories: (1) spectral analysis, including line and continuum fitting, redshift and reddening correction, spectral arithmetic and convolution, equivalent width and flux calculation; and (2) spectral energy distribution fitting, which implements optimized SED fitting. VOSpec provides multiple display modes and a stable, reliable spectral processing capability, and can conveniently integrate metadata from different data providers, such as physical units. It supports the IVOA’ s Simple Application Messaging Protocol (SAMP), enabling convenient collaboration with other Virtual Observatory applications. The current latest version is 6.6. The spectral analysis interface is shown in Figure 1, and the SED fitting interface is shown in Figure 2.

2.2 VOSED

VOSED[5] is an online tool developed by the Spanish Virtual Observatory for synthesizing spectral energy distributions. It can query spectral information from Virtual Observatory spectral services online through the Simple Spectral Access Protocol. The current version is 2.0. VOSED uses Bayesian methods to synthesize SEDs from spectral data obtained from astronomical databases or user-provided data in formats such as FITS, VOTable, and ASCII. It has two working modes: (1) Single-target mode: After users input the target name or other attributes, VOSED queries SIMBAD (an astronomical database maintained by the Strasbourg Astronomical Data Center) to display basic information about the target. Users can monitor the query status, and once completed, a compressed file containing the SED is created. (2) Multi-target mode: In this mode, the generated SEDs can also be uploaded to other Virtual Observatory tools for further visualization and analysis. The query interface and results display interface for VOSED are shown in Figures 3 and 4, respectively.

2.3 SpecView

SpecView[6] is a visualization and analysis tool developed by the Space Telescope Science Institute for analyzing spectra from the Hubble Space Telescope and other scientific instruments. It can read all HST data formats, as well as data from IUE, FUSE, ISO, FORS, SDSS, and MAST (the Mikulski Archive for Space Telescopes), plus generic ASCII format spectral data. The current version is 2.17.6. SpecView can also query and retrieve data through Virtual Observatory services. Users can conveniently complete spectral analysis tasks with just a few mouse clicks. Its visualization features include data quality control, spectral unit conversion, Boxcar and Gaussian smoothing, spectral feature extraction and display, and customizable visualization parameters. Processing results can be saved as VOTable files. The software query interface is shown in Figure 5, and the main interface is shown in Figure 6. SpecView is primarily used for creating broad-band spectral energy distributions, allowing overlay or merging of astronomical data from different instruments or bands. It can also overlay line identifications from different line libraries or user-provided line lists. Multiple theoretical models are provided for user selection, or users can provide their own models. SpecView has spectral fitting capabilities.

Graphical Interface Application Software for Analyzing Broad-band Spectral Energy Distributions

2.4 Iris

Iris[7] is a graphical application for analyzing broad-band spectral energy distributions, initially developed by the US Virtual Observatory (2011-2014) and later continued by the Chandra X-ray Observatory. The current version is 2.0. Iris supports standard SED data formats including VOTable and FITS, as well as extragalactic data formats. Non-standard formats can be converted using the tool' s data conversion module. Iris can read photometric data from multiple individual data sources or catalogs, which can come from different astronomical instruments. It then fits the SED using emission and absorption spectral models. Iris can query the NASA/IPAC Extragalactic Database (NED) registered with the Virtual Observatory. The tool provides data visualization preferences and display options. The NED query interface is shown in Figure 7, and the SED visualization interface is shown in Figure 8. Iris' s user interface is similar to SpecView' s visualization and analysis interface. One of its main functions is creating multi-band SEDs. When creating SEDs, users may input data in multiple file formats. To solve this, Iris includes a conversion tool that transforms user data into standard formats including ASCII, CSV, FITS, IPAC, and TST. Users can also create redshifted SEDs given a redshift value, or create SEDs through interpolation algorithms. The SED analysis and manipulation toolkit includes Sherpa, a Python-based extensible application for multi-band modeling and fitting for astronomers.

Spectral Analysis Tools with Full Collaborative Platform Support

2.5 SPLAT

SPLAT[8] is a graphical tool specifically designed for spectral analysis. The current version is 3.11-1. Originally developed as STARJAVA for the StarLink project, it is now maintained by Peter Draper from the German Astrophysical Virtual Observatory (GAVO) team and the Astronomical Institute of the Czech Academy of Sciences, who have extended its functionality to interoperate with other Virtual Observatory tools and services. SPLAT consists of two parts: one is the Simple Spectral Access Protocol for querying and downloading spectra, and the other is the Simple Application Messaging Protocol for desktop use, enabling interaction with other Virtual Observatory tools. SPLAT can read multiple spectra simultaneously and display them individually or collectively. The spectral visualization interface is shown in Figure 9. Features include zooming and scrolling display windows, local display at specific wavelengths, polynomial fitting, Lorentzian fitting, and Voigt fitting of selected emission and absorption lines, as well as spectral filtering using mean, linear window functions, and wavelet denoising. SPLAT fully supports coordinate display and can convert between coordinate systems to maintain consistency. It incorporates the latest features from the Starlink library.

2.6 CASSIS

CASSIS[9] is an interactive spectral analysis software developed by the French Space Astrophysics Laboratory (CESR) and the Institute for Research in Astrophysics and Planetary Science (IRAP). The latest version is 3.8. Like other Virtual Observatory tools, it uses the Simple Spectral Access Protocol to query spectra from IVOA-registered services, including data from Hubble, Corot, Spatialogue, and ISO, and uses the Simple Application Messaging Protocol for data exchange and interoperability between different astronomical software. CASSIS can construct theoretical spectra for any telescope by querying local databases for line input and using internal models including JPL+NIST, CDMS, and LTE (Local Thermodynamic Equilibrium) models. These models are continuously updated. Users can specify spectral resolution, build simulated spectra through the models, compare them with observational data, estimate physical parameters such as column density and excitation temperature, and save fitted lines. The query interface is shown in Figure 10, and the spectral visualization interface is shown in Figure 11.

2.7 ASERA

ASERA (A Spectrum Eye Recognition Assistant) is an interactive spectral identification software developed by the National Astronomical Observatories, Chinese Academy of Sciences, based on JAVA. The latest version is ASERA 2.0. It is designed to help users identify quasar spectra and measure redshifts, but is not limited to quasars; it can also handle galaxies and active galactic nuclei. The toolkit has two modes: (1) Independent application: Users can easily identify spectra and estimate redshifts, improving classification accuracy, especially for low-quality spectra. Spectral lines move with the mouse cursor, and redshift values are automatically provided. Input files can be from LAMOST or TXT format, and users can load their own templates. (2) Batch processing: Can process multiple spectra simultaneously, with Gaussian fitting of lines. The main interface is shown in Figure 12 [Figure 12: see original paper].

Comparison of Software

Comparison of seven spectral analysis software tools

Software	Key Features	Recommended Environment
VOSpec	Spectral and continuum fitting, redshift and reddening correction, spectral arithmetic and convolution, multiple display modes	Application/Windows/Linux/Mac OS X
VOSED	Data from large spectral databases, two query modes	Website
SpecView	Data quality control, spectral unit conversion, customizable visualization parameters, spectral feature extraction and display, multiple spectral overlay	Application/Windows/Linux/Mac OS X
Iris	NED data visualization and customization, spectral model fitting, irregular data format conversion	Application/Linux/Mac OS X
SPLAT	Multiple fitting functions, spectral denoising filters	Application/Windows/Linux/Mac OS X
CASSIS	Theoretical spectral construction, comparison of telescope data with various model spectra, estimation of spectral physical parameters	Application/Windows/Linux/Mac OS X
ASERA	Automated redshift measurement, customizable visualization	Application/Windows/Linux/Mac OS X

Summary and Outlook

Through the introduction, analysis, and comparison of commonly used spectral analysis software, we find that VOSpec, VOSED, SpecView, Iris, SPLAT, and CASSIS all support the Simple Spectral Access Protocol, enabling access to spectral data from Virtual Observatory-registered databases such as NED, VizieR, ESO, and SIMBAD, or from spectroscopic survey telescopes. They also support the Simple Application Messaging Protocol for data exchange and interoperability between software. All support SED synthesis, visualization, and analysis. ASERA has the unique function of automated spectral recognition and line identification that the other six software lack. Most of these tools can be integrated as web-based applications or small programs written in various languages, making them suitable for integration on a single platform for more convenient use and data exchange, thus becoming more powerful. Each software has its own advantages, disadvantages, and unique features. Through the above introduction and description, astronomers can select appropriate tools based on their needs and research goals. Examples include China' s China-VO DAMEWARE[11-12], which facilitates secondary development and addition of new functions. With more spectroscopic surveys producing increasingly large datasets, the demand for automated spectral analysis and processing is growing stronger. As astronomers apply these software tools and provide timely feedback, and through good interaction between astronomers and software developers, spectral analysis software will become increasingly convenient, powerful, and robust, enabling astronomers to handle spectra more skillfully and efficiently, thereby driving great progress in astronomical research.

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Note: Figure translations are in progress. See original paper for figures.